LA-UR-91- 2802

LA-UR--91-2802

DE91 018006

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SUBMITTED TO: 4th International Conference on Ion Sources
Bensheim, Germany
September 30 - October 4, 1991

Conference Proceedings to be Published in a Special Issue
of the Review of Scientific Instruments

H^- TEMPERATURE DEPENDENCIES IN A PENNING SURFACE-PLASMA SOURCE

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Abstract

Simple analysis of the nearly-Maxwellian angular distributions of the ribbon H^- ion beams extracted from a long, narrow slit on the 8X source yields the H^- temperature, kT_{H^-}. The derived kT_{H^-} are 0.1-0.3 eV for a 2-A dc discharge and 0.7 1.3 eV for a 400-A pulsed discharge. Because this diagnostic method relies on simple electronic techniques, it allows rapid study of the dependencies of kT_{H^-} on the source parameters, such as gas flow and discharge current. These variations of kT_{H^-} in the 8X source are qualitatively similar to those observed for the H-atom temperature, kT_{H^0}, in the 4X source, another Penning surface-plasma source.

I. Introduction

One of the important parameters of the H^- beam from an ion source is the emittance, which is ultimately limited by the H^- plasma temperature kT_{H^-}. Spectroscopic measurements show that for Penning surface-plasma sources (SPS) kT_{H^0} is 0.2 eV for low current dc discharges[1] and 0.6–3 eV for high current pulsed dis-charges.[1-3] If the H^- ions assume the H-atom temperature before extraction,[4] intrinsic kT_{H^-} from 0.2 to 3 eV may be expected. To determine kT_{H^-} in our Penning SPS discharge, we use the slit-diagnostic technique.[5]

II. Experimental Method

The slit diagnostic technique, described in detail in Ref. 5, is based on ion-optical considerations and the use of an emittance-measuring device.[6] The cathode-cathode and anode-anode gaps within the 8X source[7] are both 3.40 cm (Fig. 1). A slit ion optical system allows the emitting plasma to be examined in either the cathode-to-cathode (parallel to the magnetic field) or anode-to-anode (perpendicular to the magnetic field) directions. A schematic of the experimental arrangement with the anode-to-anode orientation of the slit extraction system is shown in Fig. 1 of Ref. 5. With a Gaussian fit routine we determine the FWHM of the angular distribution of the extracted H^- ions, θ_{FWHM}, and then infer the inherent kT_{H^-} in the source plasma using $kT_{H^-} =$

$0.361\ \phi_b\ (\theta_{FWHM})^2$, where ϕ_b is the beam energy . Sample angular distribution data near the center of the ribbon beam are shown in Fig. 4 of Ref. 5 for both a high-current, pulsed discharge and a low-current, dc discharge.

III. Results

The 8X source parametric dependence of kT_{H^-} on the H_2 filling pressure P_{Fill}, for fixed discharge current $I_d = 460$ A and magnetic field $B_x = 290$ G, is shown in Fig. 2a. The dc H_2 pressure in the source chamber before the 5-Hz, 1.2-ms-long arc pulse is ignited is P_{Fill}: P_{Fill} is calculated from the measured dc H_2 gas flow Q_{H2} and the calculated H_2 conductance, assuming a temperature of 500 °K. For comparison purposes, previous measurements of kT_{Ho} vs P_{Fill} for the 4X source, in both the drift region (adjacent to the emitter) and the plasma column, are shown in Fig. 2b.

Figure 3a shows kT_{H^-} vs the discharge current I_d, for fixed H_2 filling pressure = 0.054 Torr and magnetic field B_x = 290 G, for the 8X source. Figure 3b shows previous kT_{Ho} vs I_d measurements for the 4X source obtained from both emission[1] and absorption spectroscopy.[2] The absorption spectroscopy kT_{Ho} values[2] for the 4X source (both the measurements for the drift region and the plasma column) are obtained in the y direction, perpendicular to the beam direction, z, and the magnetic field direction, x. The emission spectroscopy kT_{H0} values[1] are an average along the H^- beam direction, z, through the drift and the plasma column.

The dependencies shown in Figs. 2a and 3a are for 300- to 500-A pulsed 8X source discharges. We also have measured kT_{H^-} as a function of the various 8X source parameters for 2- to 4-A dc discharges. The dependence of kT_{H^-} on P_{Fill} is shown in Fig. 4 for both the anode-anode and the cathode-cathode diagnostic-slit orientations.

IV. Discussion

To compare the H-atom measurements on the 4X source with the H^- measurements on the 8X source, we need guidance on the scaling between the two sources. We use the predictions of the similarity law as expressed by Muehe:[8] if the source linear dimensions are increased by the factor K_1 ($\approx$2 for the 8X source) and the magnetic field and gas flow are scaled down by the same factor K_1, then the discharge will have the same voltage if the current density of the larger source is reduced by the factor $1/K_1$. Then the other particle densities in the larger source will be reduced by the same factor $1/K_1$. The temperatures of the various species will also be the same in the two sources. We have one slit diagnostic technique measurement for a pulsed discharge in the 4X source which gives kT_H 1.0 eV, about the same as for the

8X source. We have not measured kT_{Ho} in the 8X source, but we note that kT_{Ho} is approximately the same in the small-angle source (the 1X source) as it is in the 4X source.[1] In order to compare kT_{H-} in the 8X source with kT_{Ho} in the 4X source, the 8X pressure scale in Fig. 2a is double the 4X pressure scale in Fig. 2b.

The kT_{H-} decrease with increasing 8X source pressure is consistent with an exponential dependence on pressure, just as the kT_{Ho} decrease with increasing 4X source pressure is (Fig. 2). However, kT_{H-} and kT_{Ho} decrease at different rates with source pressure, partially because of differences in the energy-exchange cross sections. At P = 0.1 Torr, kT_{H-} = 0.73 eV, whereas at the scaled pressure = 0.2 Torr, kT_{Ho} = 0.66 eV, about a 10% difference.

To calculate the characteristic lengths L_{-2} and L_{o2} for energy exchange of H^- and H^o on H_2, we use L = $1 / [n_{H2} (4/5) \sigma]$ where σ is the energy loss cross section. We assume that the H_2 molecules have a temperature close to the source walls, 500 °K, and calculate n_{H2} at typical operating pressures, 0.1 Torr and 0.2 Torr for the 8X and 4X sources respectively. Using σ_{o2} = 7.4 x 10^{-16} cm^2 for kT_{Ho} = 0.75 eV and σ_{-2} = 1.22 x 10^{-15} cm^2 for 0.75 eV H

(Ref. 9) we get $L_{-2} = 1.0$ cm for the 8X source and L_{o2} = 0.8 cm for the 4X source. From the scaling law we expect L_{o2} = 1.6 cm for the 8X source. For 100 eV H^- on H_2 we estimate that L_{-2} = 27 cm, where for this case σ_{-2} includes both elastic and inelastic processes.

The characteristic length L_{-o} for energy exchange between H^- ions of ≈100 eV (from the 8X source cathodes) and H^o atoms of ≈ 1 eV in the plasma column is difficult to estimate since we do not know the cross section σ_{-o} for energy exchange. We can estimate the mean-free path of H^- in H^o, λ_{-o}, from $\sigma_{-o}^{-1} n_{Ho}^{-1}$, where σ_{-o} is the cross section for resonant charge exchange. The measured value of n_{Ho} is 3.8×10^{14} cm^{-3} for the drift and 7.3×10^{14} cm^{-3} for the plasma column in the 4X source [Ref. 2]; we use half these values for the 8X source. Using $\sigma_{-o} = 5.27 \times 10^{-15}$ cm^2 for 99 eV H^- [Ref. 10] gives λ_{-o} = 1.0 cm in the 8X drift and 0.5 cm in the plasma column. Since $L_{-2} \approx 50\,\lambda_{-o}$ for 100 eV H^-, the H^- ions emitted from the cathodes are cooled by the H^o in the source discharge. However, once the H^- cool to 1 eV, then $L_{-2} \approx L_{o2}$. Thus, the H^o and H^- appear to have the same temperature because the fast (cathode) H^- are first cooled by resonant charge exchange with slow H^o in the discharge, then the slow H^- and the remaining slow H^o are cooled by the collisions with H_2.

To compare the dependence of kT_{H^-} on the discharge current in the 8X source with the dependence of kT_{Ho} on I_d in the 4X source, we have to account for the different emission-current densities j_{H^-} between the two sources. From the similarity law, we expect the source operation to be the same if $j_{H^-}(4X)$ is adjusted to be double $j_{H^-}(8X)$. Thus, if the 8X source is equipped with an emitter that has double the area of the 4X source emitter, and if the 4X source discharge current is half the 8X source discharge current, the two sources should produce the same H^- current. To compare the 4X source kT_{Ho} dependence on I_d with the 8X source kT_{H^-} dependence on I_d, we have doubled the 4X source I_d scale in Fig. 3b.

From Fig. 3, at I_d = 400 A, kT_{H^-} = 0.93 eV for the 8X source, whereas kT_{Ho} – 0.7 eV at I_d = 200 A (the scaled current) for the 4X source, about a 25% difference. The dependence of kT_{H^-} on I_d in the 8X source appears to be linear (Fig. 3a), whereas the dependence of kT_{Ho} on I_d in the 4X source plasma column appears to be something like $I_d^{1/2}$ (Fig. 3b). However, H^- ions are not extracted from the plasma column, they are extracted from the drift region (the "dead space" between the plasma column and the emitter). The dependence of kT_{H^o} on I_d in the 4X source drift has not been measured at current values low enough to distinguish between a linear dependence and a square-root dependence.

The dependence of kT_{H^-} on the pressure in the 8X source for a low-current, dc discharge is shown in Fig. 4. The typical operating pressure for a 2.4-A dc discharge in the 8X source is 0.09 Torr, and the typical kT_{H^-} is 0.2 eV (Fig. 4). For the 8X source 2.4-A dc discharge, the characteristic length for energy exchange $L_{-2} = 0.6$ cm. For 100 eV H^- on H_2, $L_{-2} = 49$ cm. For a 1-A dc discharge, kT_{H^o} in the 4X source is ≈ 0.27 eV (Ref. 1). For 0.27 eV H^o in the 8X source, $L_{o2} = 1.2$ cm. Assuming that n_{H^o} is $\approx 1 \times 10^{13}$ cm^{-3} for the 2.4 A dc discharge,[2] the mean-free path for resonant charge exchange $\lambda_{-o} \approx 19$ cm.

V. Conclusions

Thus, in both the 2-A dc and the 350–500 A pulsed discharges, once the fast (cathode) H^- are cooled by resonant charge-exchange on slow H^o, the resulting slow H^- and the remaining slow H^o are further cooled to nearly the same temperature by collisions with H_2. The characteristic lengths for cooling, L_{-2} and L_{o2}, are comparable to the source discharge size. The H^- temperature in the 8X source is comparable to the H^o temperature in the 4X source, in agreement with the predictions of the scaling law.

Acknowledgements

The authors thank David R. Schmitt for experimental assistance and Eric J. Pitcher for comments on the manuscript. This work was supported by the Department of Defense, US Army Strategic Defense Command under the auspices of the US Department of Energy.

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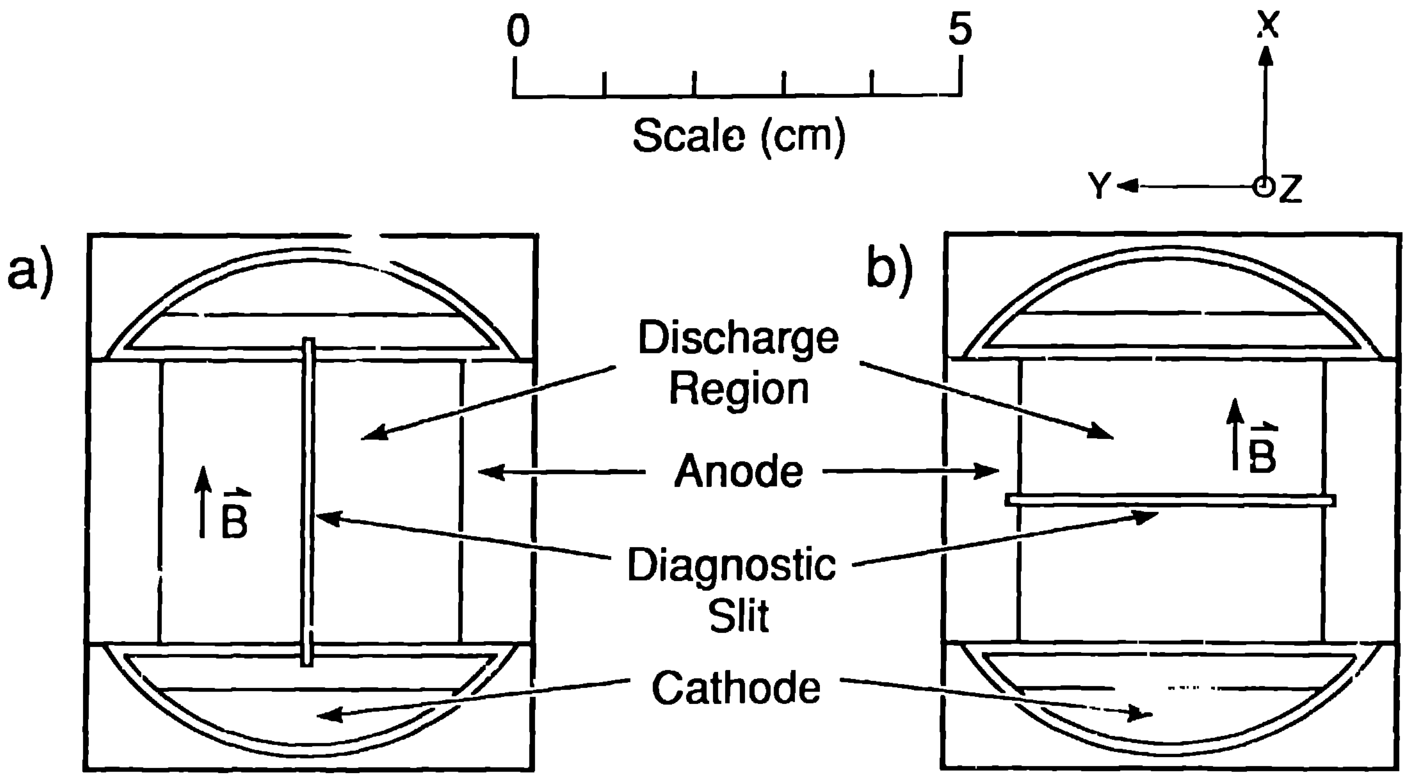
Figure Captions

Fig. 1. The 8X source geometry (+z is the beam direction). In a) the diagnostic slit is aligned along the x-direction from cathode to cathode; in b), along the y direction from anode to anode.

Fig. 2. a) The kT_{H^-} vs P_{Fill} data for the anode-anode (open circles) and cathode-cathode (filled triangles) slit orientations in the 8X source. The measured dc Q_{H2} is also given. The curve (formula in the figure) is a least-squares fit to all the data. b) The dependence of kT_{HO} on P_{Fill} for the 4X source[2] for the plasma column (open squares) and the drift (open triangles). The measured dc Q_{H2} is also given. The curves (formulae in the figure) are least-squares fits to the data.

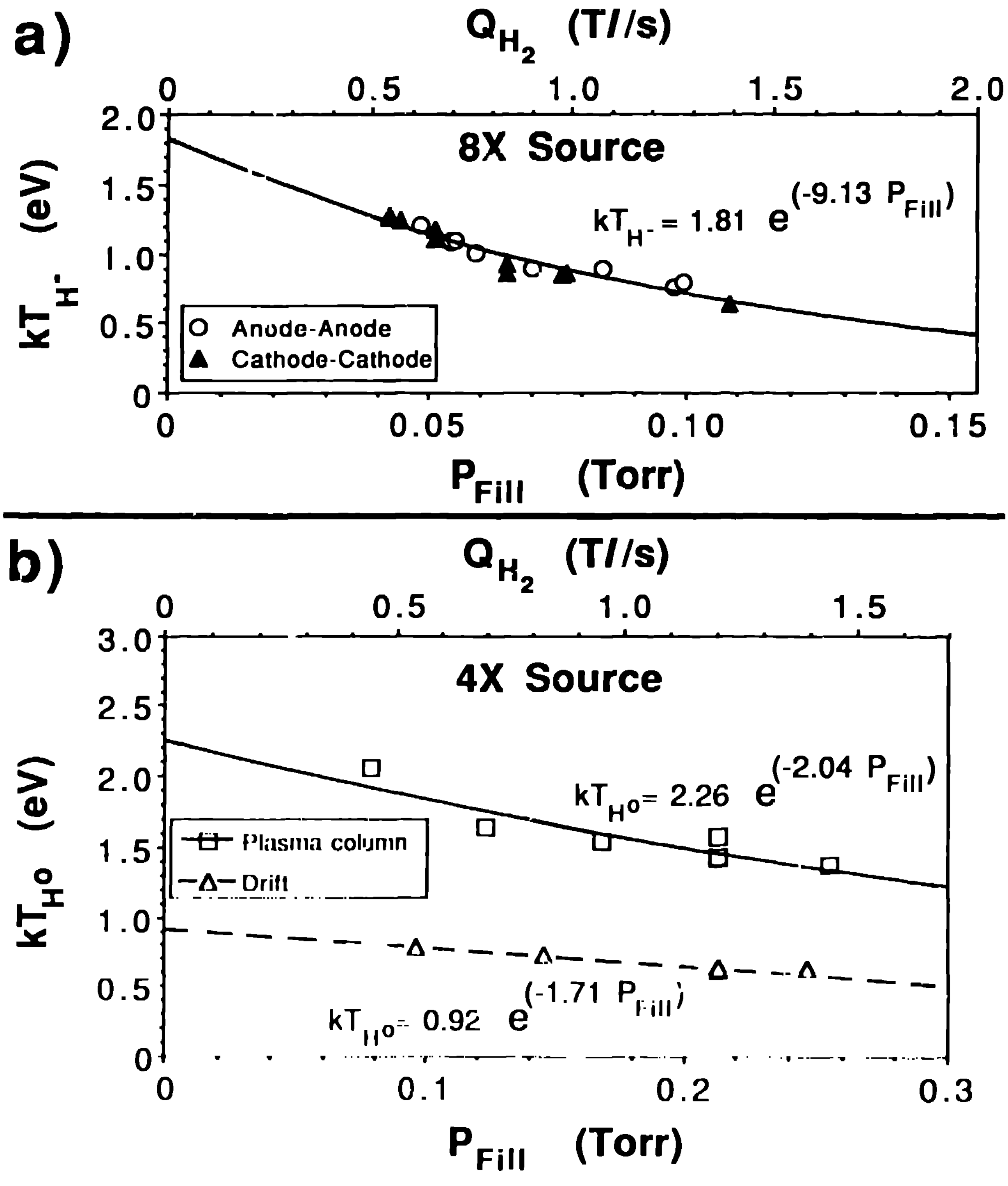
Fig. 3. a) The dependence of kT_{H^-} on I_d for the 8X source for the anode-anode slit orientation and a pulsed arc (open circles) and for the cathode-cathode slit orientation and a dc arc (filled triangle). The curve (formula in the figure) is a least-squares fit to all the data. b) The dependence of kT_{HO} on I_d for the 4X source measured by absorption spectroscopy (Ref. 2) for the plasma column (open squares) and the drift (open triangles). The dependence of kT_{HO} on I_d for the 4X source measured by emission spectroscopy (Ref. 1) is also shown (closed squares). The curves (formulae in the figure) are fits to the data.

Fig. 4. The dependence of kT_{H^-} on P_{Fill} for the anode-anode (circles) and cathode-cathode (squares) slit orientations in the 8X source with 2.0 to 2.8 A dc discharges. The measured dc Q_{H2} is also given. The curve (formula in the figure) is a least squares fit to all the data.



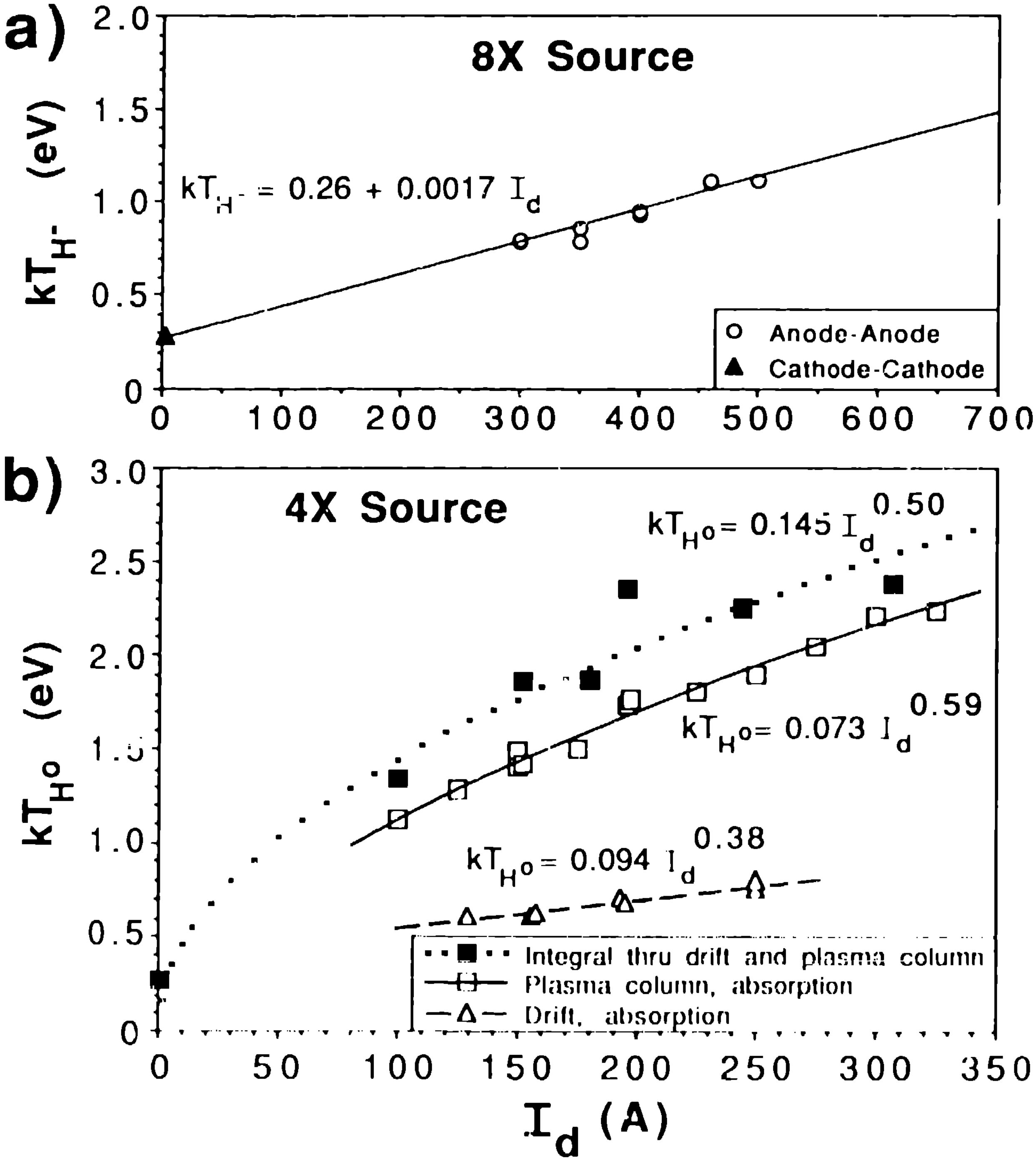
0
5
Scale (cm)
X
Y
Z
a)
b)
Discharge
Region
Anode
Diagnostic
Slit
Cathode
B
B

Figure 1



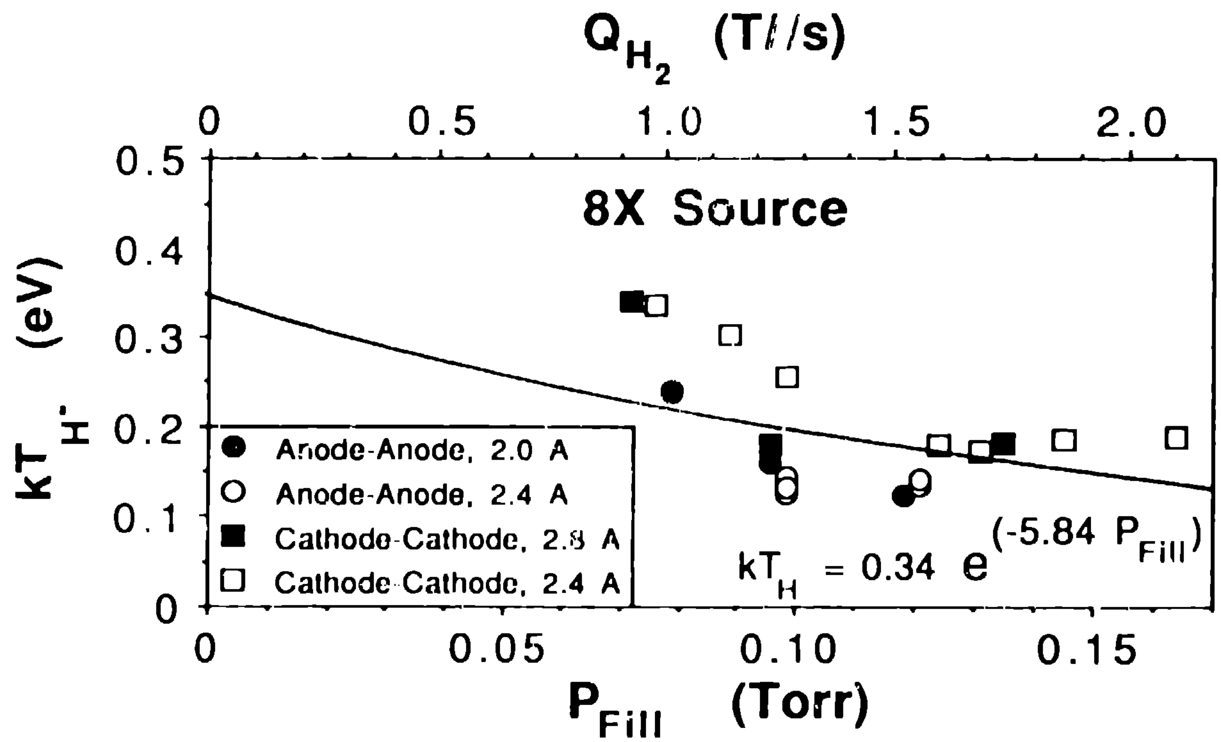
a)
b)
8X Source
4X Source
Q_{H_2} (T l/s)
P_{Fill} (Torr)
kT_{H^-} (eV)
kT_{H^o} (eV)
$kT_{H^-} = 1.81\ e^{(-9.13\ P_{Fill})}$
$kT_{H^o} = 2.26\ e^{(-2.04\ P_{Fill})}$
$kT_{H^o} = 0.92\ e^{(-1.71\ P_{Fill})}$
Anode-Anode
Cathode-Cathode
Plasma column
Drift

Figure 2



a)
8X Source
$kT_{H^-} = 0.26 + 0.0017\ I_d$
kT_{H^-} (eV)
Anode-Anode
Cathode-Cathode
b)
4X Source
$kT_{H^o} = 0.145\ I_d^{0.50}$
$kT_{H^o} = 0.073\ I_d^{0.59}$
$kT_{H^o} = 0.094\ I_d^{0.38}$
kT_{H^o} (eV)
Integral thru drift and plasma column
Plasma column, absorption
Drift, absorption
I_d (A)

Figure 3



Q_{H_2} (T/l/s)
0
0.5
1.0
1.5
2.0
8X Source
kT_{H^-} (eV)
0.5
0.4
0.3
0.2
0.1
0
Anode-Anode, 2.0 A
Anode-Anode, 2.4 A
Cathode-Cathode, 2.8 A
Cathode-Cathode, 2.4 A
$kT_H = 0.34\ e^{(-5.84\ P_{Fill})}$
0
0.05
0.10
0.15
P_{Fill} (Torr)

Figure 4